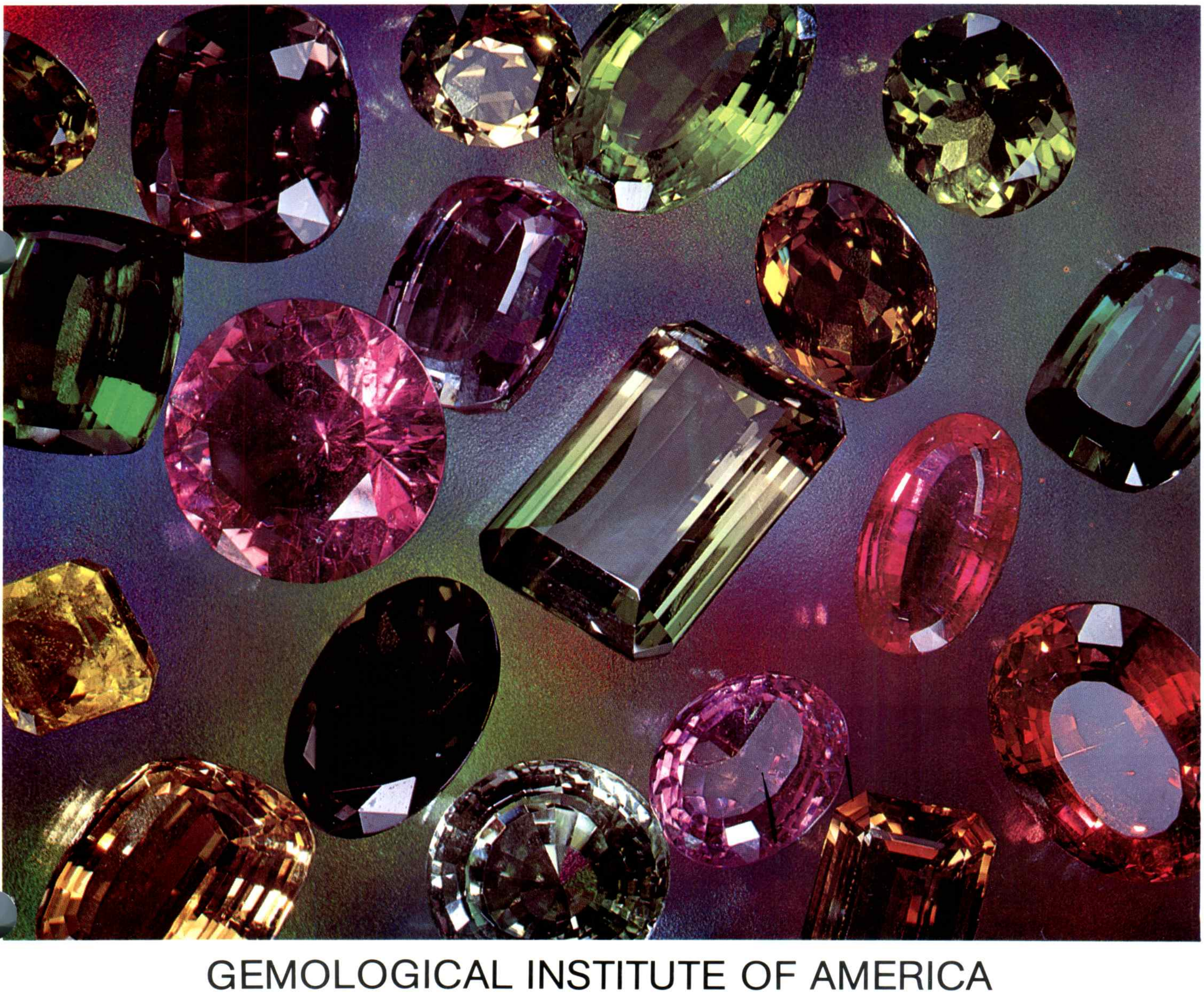
COLORED STONES
ASSIGNMENT 7
BRILLIANCY AND DISPERSION

IDENTIFICATION, PRODUCTION, MARKETING, BUYING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I. INTRODUCTION.

The last assignment explained how light is affected when it strikes the surface of a gem; i.e., part is reflected from the surface and the remainder is refracted into the gem.

We are now concerned with the behavior of light that ENTERS a stone. It is this light that accounts for a gem's dispersion, or "fire," (the flashes of rainbow colors), most of its brilliancy (the proportion of light the stone is capable of returning to the eye), and most of its body color; in short, its BEAUTY. These properties depend on style of cutting, proportions, perfection of polish, refractive index, and orientation of the stone in relation to its crystallographic axes--factors that are controlled by the cutter. A trained gemologist is able to look at a stone and, with the aid of a few simple tests, determine the extent to which cutting has exploited its inherent beauty. To accomplish this, the gemologist must understand light and its behavior in a stone as well as various optical properties which are the characteristic for each gem species. The following discussion of critical angle and total reflection is important not only for an understanding of the cause of beauty in a gem, but it concerns the theory underlying many of the tests and equipment used in the identification of gemstones.

II. CRITICAL ANGLE.

In order to understand the behavior of light, it is necessary to understand certain terms and definitions.

A. The NORMAL is an imaginary line drawn perpendicular to the surface of the material that the light is entering or leaving. (It is drawn at the point at which the light strikes the surface.)

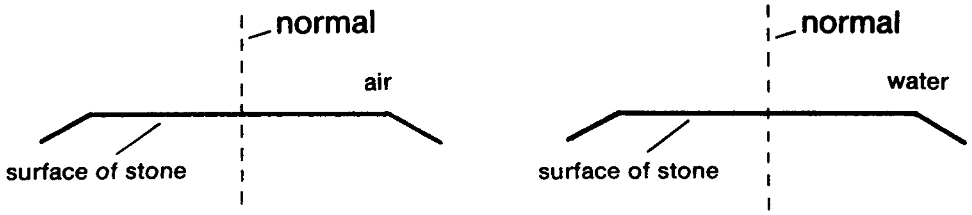

Figure 1

B. The light striking a surface is known as INCIDENT light.

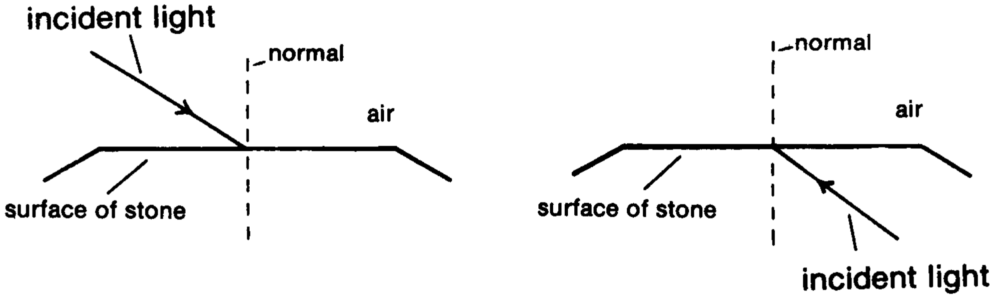

Figure 2

C. The ANGLE OF INCIDENCE is defined as the angle measured from the normal to the incident beam of light.

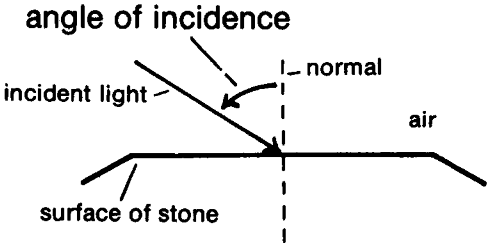

Figure 3

D. Light that bounces back after striking a surface is known as REFLECTED light.

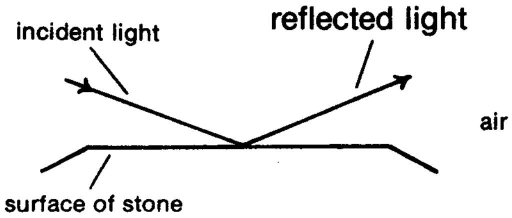

Figure 4

E. The ANGLE OF REFLECTION is the angle measured from the normal to the reflected beam of light. The angle of reflection and the angle of incidence are always equal.

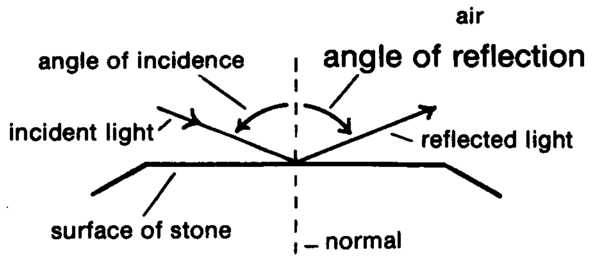

Figure 5

F. Light that is bent on entering or leaving a more optically dense material is called REFRACTED light as discussed in the last assignment.

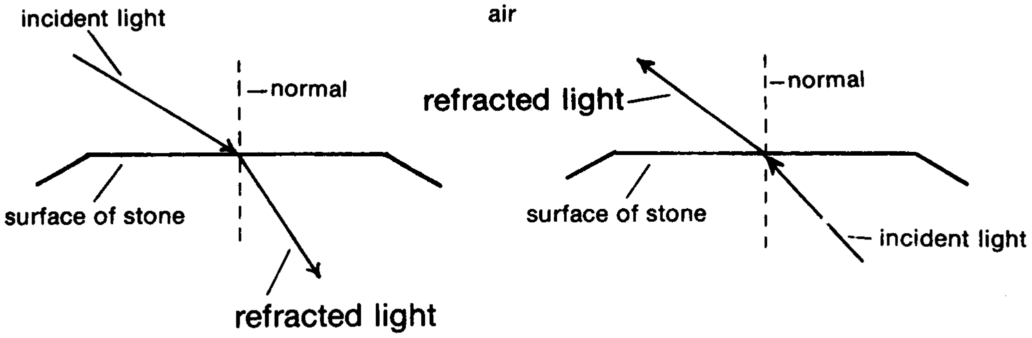

Figure 6

G. The ANGLE OF REFRACTION is the angle measured from the normal to the refracted beam of light.

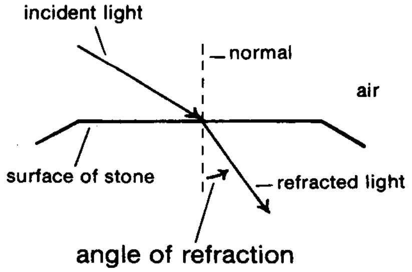

Figure 7

The path that light takes as it leaves the stone is the same it would have taken on entering the stone. In other words, to determine the behavior of light leaving a gem, it is only necessary to reverse the direction of the light in the diagram.

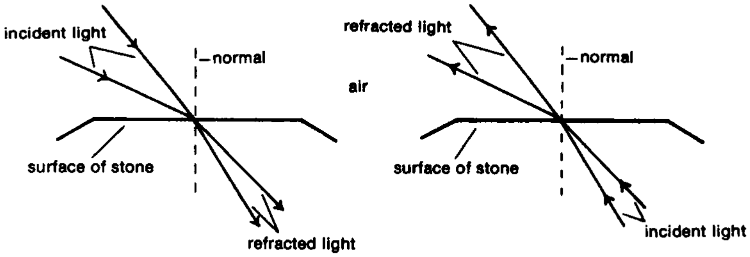

Figure 8

It was shown in Assignment #6 that the direction of light entering a gemstone from the air perpendicular to the surface is unchanged as the light enters the stone: the light is merely slowed down. Light striking at any angle other than perpendicular to the surface is bent (refracted) on entering the stone. The greater the angle of incidence, the more the light is bent when it enters the stone.

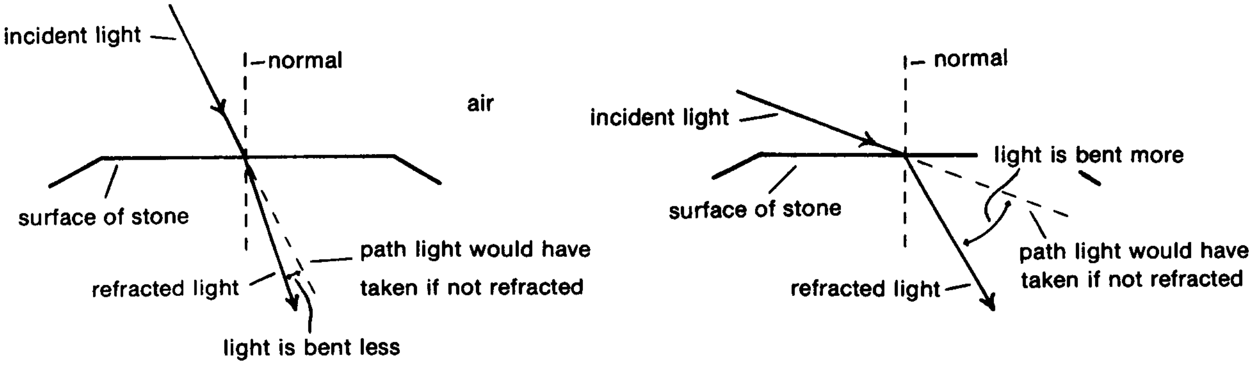

Figure 9

When the beam just grazes the surface, it is subject to maximum bending when refracted into the stone.

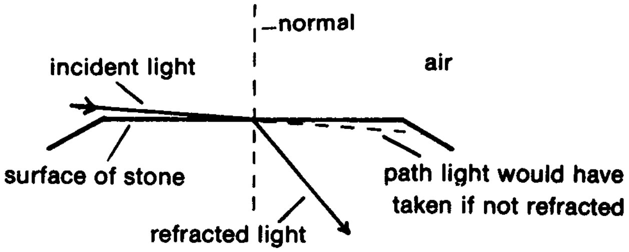

Figure 10

The angle formed between this refracted beam of light (beam 1) and the normal is the largest angle of refraction that can be formed within the stone. All light entering the stone will be refracted into the stone at this angle or a smaller angle of refraction.

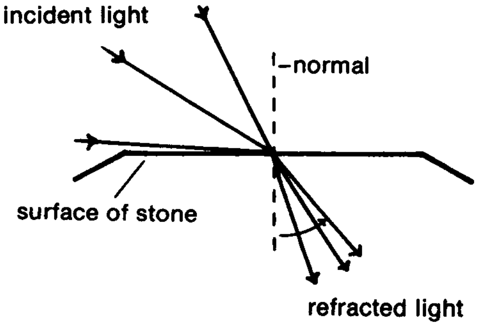

Figure 11

Since the angle of refraction formed by the beam of light that just grazes the surface of the stone is the largest angle of refraction formed within the stone, and all other light entering the stone falls within this angle, reversing the direction of the light shows that only the light striking the internal surface of the stone within this angle will be able to leave the stone. This is called LEAKAGE.

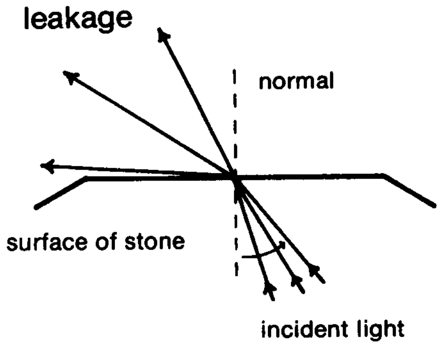

Figure 12

Light striking the internal surface of the stone at an angle larger than that formed by the refraction of the beam of light just grazing the surface will be totally reflected inside the stone.

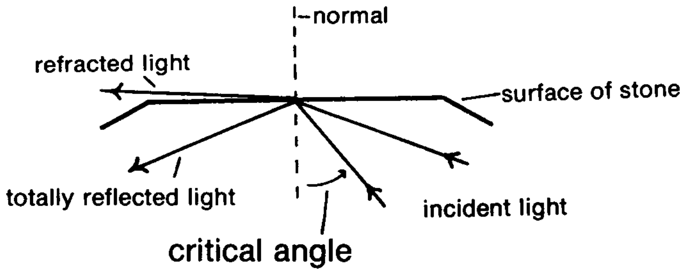

Figure 13

Since the angle formed by the last beam of light just grazing the outer surface of the stone tells us which light will be refracted out of the stone and which light will be totally reflected within the stone, it is called the CRITICAL ANGLE. Gem cutters use their knowledge of the critical angle to decide which angles to use in cutting the facets of the stone. The following diagram will help you to understand why this is so important.

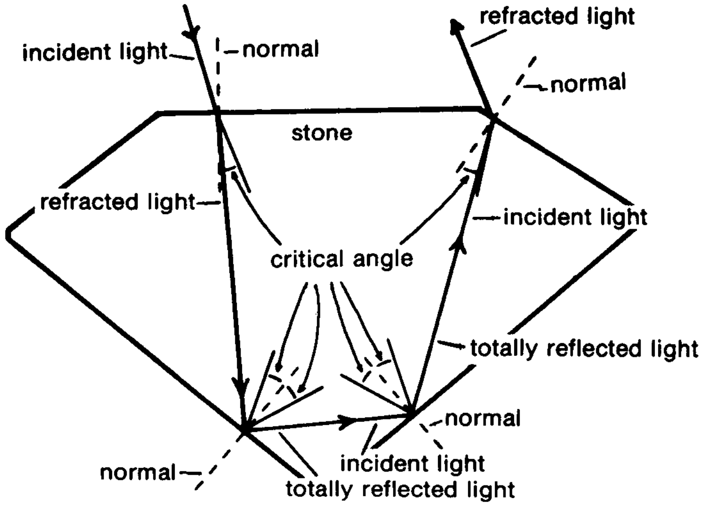

Figure 14

As shown in Figure 14, most faceted stones are cut so that light enters from the crown is reflected off the pavilion facets and directed back through the crown to the eye. The light that is returned to the eye in this way is called BRILLIANCE. A stone such as diamond is very brilliant since it returns a large portion of the light that enters it back to the eye. If the angles, on the pavilion facets in particular, are not cut correctly, light hitting the pavilion will fall within the critical angle and leave the stone through the pavilion facets. This is called UNPLANNED LEAKAGE. When this happens, it is possible to look right through the stone. Such a stone is said to have a window. You should not be able to see through a well-cut stone when looking through the table.

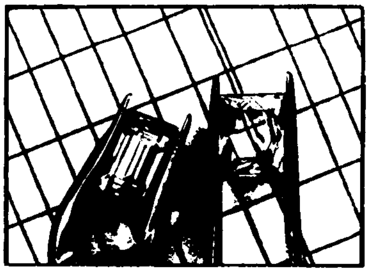

Figure 15

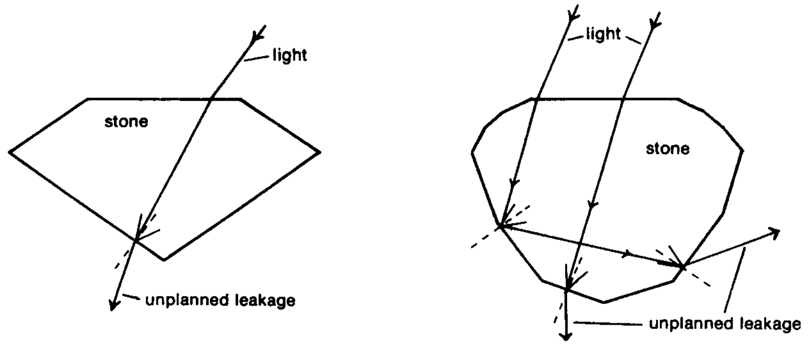

Figure 16

Light will also leak out of the pavilion facets if the stone has a large critical angle. The size of the critical angle depends on the ability of the stone to bend light. The more the light is bent by the stone, the smaller the critical angle. The higher the refractive index of a stone, the more light is slowed down and bent as it enters the stone. Thus, the HIGHER THE REFRACTIVE INDEX, THE SMALLER THE CRITICAL ANGLE and THE LOWER THE REFRACTIVE INDEX, THE LARGER THE CRITICAL ANGLE. This means that a stone with a low refractive index (such as quartz) will leak more light through the pavilion facets and appear less brilliant than a stone with a high refractive index (such as diamond).

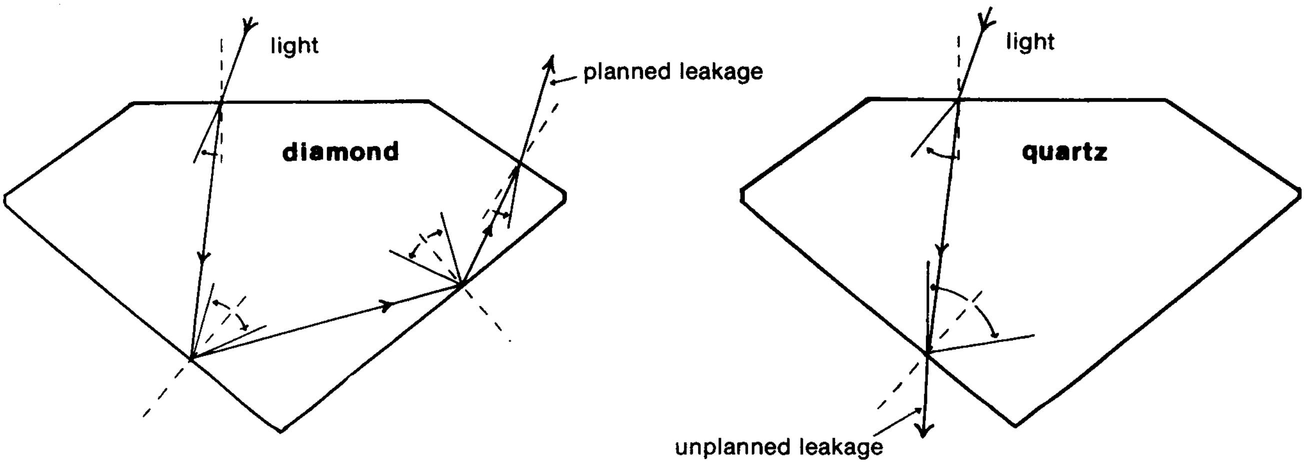

Figure 17

The critical angle is also the reason that a stone should be well polished to show maximum brilliance. An irregular surface will form critical angles in all directions as shown in Figure 18. More light will hit the surface within the critical angle and be leaked out of the stone and not returned to the eye. A flat surface, on the other hand, will only allow light approaching from certain directions to fall within the critical angle. By cutting the pavilion facets at the proper angles, the light leaking out the pavilion of a well-polished stone can be kept at a minimum.

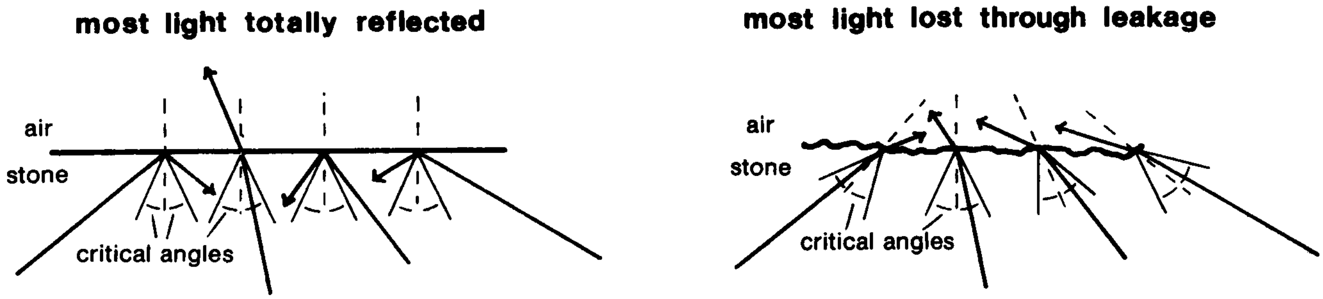

Figure 18

Accompanying this Assignment is a list of stones with their refractive indices and critical angles. The critical angle of a stone is computed mathematically by the formula:

$\sin i = \frac{1}{n}$ where

$\sin i$ = sine of the critical angle

n = refractive index of the stone

It is not necessary to remember either the critical angle or the formula for this course. Unless you facet stones, you will probably never need to use the critical angle for any one particular stone. The information is given here simply as a reference. The refractive indices for the major gemstones such as diamond, corundum, and quartz should be eventually memorized since the refractive index of a stone is a major key to its identification. The principle of how the critical angle affects light in a cut stone should be studied thoroughly, however.

For simplification, the illustrations used so far have been confined to cross-section drawings of stones. In actual practice, light reacts in three dimensions. In other words, light strikes the surface from all directions about a given point. This means that the critical angle would look and react more like a cone or funnel, as shown below. It can be thought of as the CRITICAL ANGLE CONE.

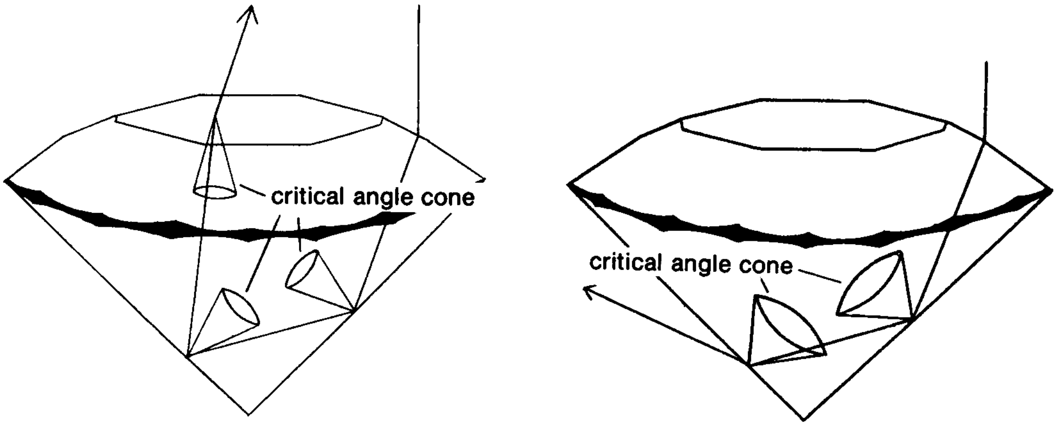

Figure 19

III. DISPERSION.

The breaking up of white light into its spectral colors is known as DISPERSION. When discussing the electromagnetic spectrum, it was noted that each of the visible hues (red, green, blue, etc.) has a different wavelength. Although light travels in air at the same velocity regardless of wavelength, when it enters a gemstone, each of the various wavelengths travels at a different speed. The shorter the wavelength, the more it is slowed down by the gem. Thus, the violet and blue wavelengths are slowed down more than the red. The more light is slowed down by a substance, the more it will bend if it enters the stone at an oblique angle. This means that the violet and blue wavelengths will be bent more than the red wavelengths.

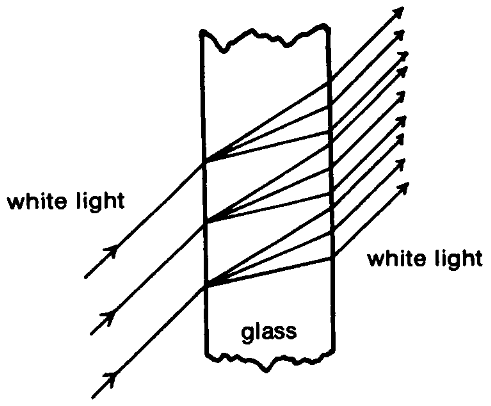

Figure 20

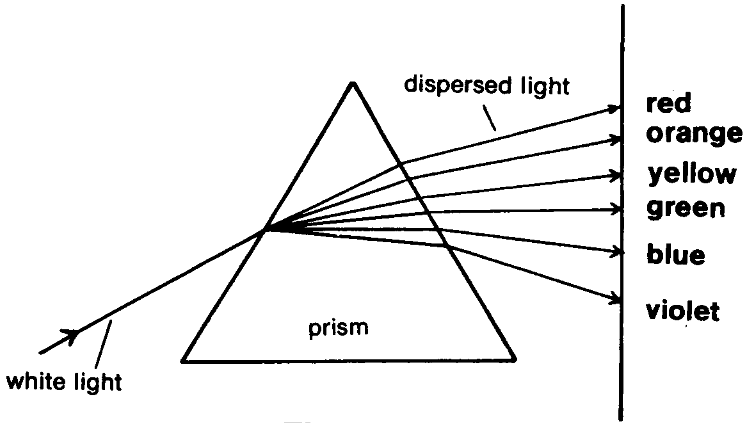

Figure 21

If the light passes through a material with parallel surfaces, such as a window, it will either go straight through or it will be broken up, depending on the angle of incidence, but the wavelengths will be returned to their original paths. They will be essentially put back together again. We see the result as white light. However, if the light passes through a prism, as shown in Figure 21, the colors will remain separated. This is why light passing through the prisms on a chandelier will cast rainbow colors (a spectrum) on an opposite wall. Water molecules in the air after it rains, or by a water fall, effect light in the same way, causing a rainbow.

Light must be bent in order for the colors to be separated. As shown in Figures 10, 11, 12 and 14 earlier in this Assignment, light is bent the most as it enters or leaves the stone along the critical angle. The more the light is bent, the more dispersion takes place. The light leaving the stone right at the critical angle will be dispersed the most. The crown facets (other than the table) are designed to allow light leaving the stone to be dispersed as much as possible.

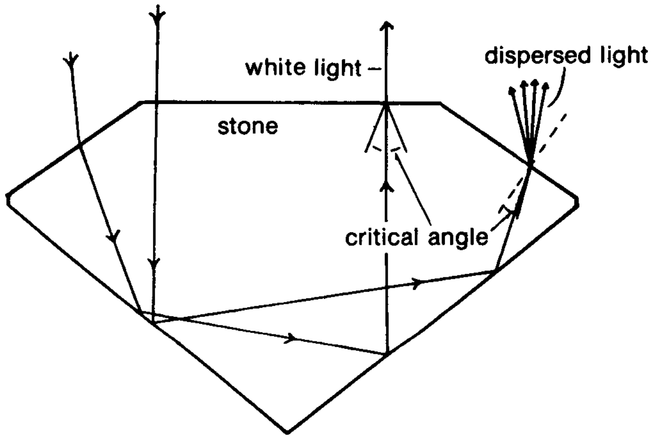

Figure 22

Since each of the wavelengths is slowed down differently in a stone, each has a separate refractive index. Dispersion is measured by the difference in the refractive indices of certain of the red and blue-violet wavelengths of light as they pass through a given material. These wavelengths are referred to as the B and G Fraunhofer lines. Each gem species has a different ability to break up light into its component colors and so, has a different dispersion. For example, the R.I.'s for the B and G Fraunhofer lines in spinel are 1.710 and 1.730, respectively. Therefore, the dispersion of spinel is .020. (The refractive index of a specific stone as listed in R.I. tables is usually given for a very narrow range of yellow light in the middle of the visible spectrum.)

In general, dispersion in gems increases with increasing refractive index. There are a few exceptions to this as can be seen by comparing the refractive index and dispersion tables accompanying this assignment. Dispersion is not noticeable in most stones but it is important in separating diamond substitutes over the limits of the refractometer (over 1.81 in R.I.). Strontium titanate and synthetic rutile have such strong dispersion that it is very easily seen. YAG, in comparison, shows almost none. Diamond, zircon, and andradite garnet show noticeable dispersion. It is not an important gemological property in separating stones with refractive indices below 1.81.

IV. SCINTILLATION.

Although scintillation is most important in diamond due to its superior reflective surfaces, it is also a factor to be considered in colored stones. Scintillation or sparkle in gemstones may be defined as the flashing of light from the facets of a stone that is seen as the gem, the light source, or the observer moves. The more movement, the more the scintillation. Also, the more facets in a stone, the more the scintillation. A maximum degree of scintillation might not produce the maximum degree of beauty, however. On small stones, a very large number of facets will increase the scintillation but the facets will be so small that the stone will have a fuzzy appearance. The most desirable condition is one somewhere between the broad flashes of light from a stone with large facets and one with facets so small that they appear fuzzy.

The sharpness and clarity of the sparkle is affected also by the quality of the polish on the facets and the proportions of the stone. The more highly polished the facets, the stronger the flashes will be.

V. CONCLUSION.

The beauty of gemstones is mainly the result of the way the gemstones affect the light that passes through them. Brilliancy, dispersion, and scintillation all contribute to the appearance of a stone. Brilliancy is probably the more generally important optical property since dispersion is only important in a very few stones and scintillation is dependent on the cut of the stone.

Any properly cut and polished transparent gemstone should appear brilliant across its entire breadth when the observer looks into the stone with the light source directly above its table. An improperly-cut stone will show a "dead" spot in the center under these conditions, and a needle or other object placed beneath the stone will be visible due to the leakage of light through the pavilion. The stone will act as a window pane rather than as a mirror. The needle will not be seen if the stone is properly cut.

Because stones with high refractive indices have a small critical angle, less light will be able to leak out the pavilion and they will return more light to the eye than stones with low refractive indices. By careful observation, with the unaided eye, of the brilliance of different stones, one can gradually begin to separate stones of higher and lower refractive indices. This is especially true in colorless stones. Colored stones, on the other hand, are more difficult at first. For example, a light-colored quartz might seem more brilliant than a much darker tourmaline of the same color. The darker tourmaline absorbs more light and, therefore, reflects less back to the eye. Another exception is synthetic rutile. Synthetic rutile is advertised as being more brilliant than diamond. Other factors being equal, this would be true, since the refractive index of synthetic rutile (2.61 to 2.90) is higher than that of diamond (2.417). However, a comparison of a well-cut diamond with a well-cut synthetic rutile will show that the diamond is more brilliant. Synthetic rutile is less transparent than diamond. It absrobs a significant portion of the light so it cannot return to the eye the high proportion of light that is returned by diamond. Furthermore, it possesses a phenomenal power of dispersion. This means that much of the light totally internally reflected does not return to the eye as white light but as spectral colors, or "fire." In addition, it is difficult, if not impossible, to polish surfaces on synthetic rutile that produce a luster even approaching that to be expected from a material of such a high R.I. Diamond takes a much finer polish. These factors more than make up the difference between the refractive indices of the two stones--causing diamond to be actually more brilliant than synthetic rutile. Generally, however, one can select a gem of any one species as being more brilliant than one of another species with a lower refractive index, assuming that both are correctly proportioned and well polished.

Since the refractive index of a stone is so important in determining its beauty, the refractive indices of the major gemstones listed in this assignment should be studied carefully. As you will begin to realize more and more as you progress in this course and the Gem Identification Course, the refractive indices are also of the utmost importance in identifying the different species. Eventually, you will be expected to know all the refractive indices on the accompanying table from memory.

REFRACTIVE INDICES
OF THE COMMON GEM MINERALS
AND RELATED SUBSTANCES

For doubly-refractive stones, the normal index for each of the doubly-refractive rays is given. For singly-refractive stones, of course, only one index is listed. Slight variations in these values may be encountered.

Pearl, coraland shell are not listed because they seldom present surfaces that are suitable for R.I. determinations. When a reading can be obtained, however, it will be at approximately 1.66, with a second possible reading as low as 1.49. In addition, remember that the R.I.'s of those materials over 1.81 cannot be obtained by usual gemological methods.

Critical angles of the transparent materials are also given. These are computed from the lower refractive index.

Species	Refractive Index	Critical Angle
Hematite	2.94 - 3.22	
Syn. Rutile	2.616 - 2.903	22°28'
Diamond	2.417	24°25'
Strontium titanate	2.409	24°32'
Cubic zirconia	2.15	27°43'
GGG	2.03	29°31'
Zircon (High)	1.925 - 1.984	31°18'
Zircon (Medium)	1.875 - 1.905	32°14'
Andradite (G)	1.875	32°14'
YAG	1.833	33°04'
Zircon (Low)	1.810 - 1.815	33°32'
Spessartite (G)	1.810	33°32'
Almandite (G)	1.790	33°58'
Corundum	1.762 - 1.770	34°35'
Syn. Corundum	1.762 - 1.770	34°35'
Rhodolite (G)	1.760	34°37'
Pyrope (G)	1.746	34°56'
Chrysoberyl	1.746 - 1.755	34°56'
TP Grossularite (G)	1.74	35°05'
TL Grossularite (G)	1.72	35°33'
Rhodonite	1.73 - 1.74	35°19'
Syn. Spinel	1.73	35°19'
Spinel	1.718	35°36'
Idocrase	1.713 - 1.718	35°43'
Zoisite	1.691 - 1.704	36°15'
Diopside	1.675 - 1.701	36°39'
Jadeite (J)	1.66 - 1.68	
Malachite	1.660 - 1.910	
Spodumene	1.660 - 1.676	37°03'
Jet	1.660	
Peridot	1.654 - 1.690	37°12'

Species	Refractive Index	Critical Angle
Andalusite	1.634 - 1.643	37°44'
Tourmaline	1.624 - 1.644	38°00'
Topaz	1.619 - 1.627	38°09'
Turquoise	1.610 - 1.650	
Nephrite (J)	1.606 - 1.632	
Rhodochrosite	1.597 - 1.817	38°46'
Beryl	1.577 - 1.583	39°21'
Syn. Emerald (Hydrothermal)	1.568 - 1.583	39°38'
Syn. Emerald (Flux)	1.561 - 1.564	39°50'
Serpentine	1.560 - 1.570	
Labradorite (F)	1.559 - 1.568	39°54'
Quartz	1.544 - 1.553	40°22'
Iolite	1.542 - 1,551	40°26'
Ivory	1.540	
Amber	1.540	40°30'
Oligoclase (F)	1.539 - 1.547	40°31'
Chalcedony	1.535 - 1.539	
Albite (F)	1.525 - 1.536	40°59'
Microcline (F)	1.522 - 1.530	
Orthoclase (F)	1.518 - 1.526	41°12'
Obsidian	1.50	41°49'
Lapis-Lazuli	1.500	
Moldavite	1.50	41°49'
Calcite	1.486 - 1.658	42°18'
Sodalite	1.483	42°24'
Opal	1.450	43°36'
Glass (Normal)	*1.48 - 1.70	
Fluorite	1.434	44°13'
Plastic	1.46 - 1.70	
Assembled	Any	

KEY TO SYMBOLS: (G) = Garnet; (F) = Feldspar; (J) = Jade; (Q) = Quartz

* The refractive index of glass may exceed 1.70, but such material is too soft for practical gem use and is therefore rarely encountered.

COLOR DISPERSION
OF THE COMMON TRANSPARENT GEM MATERIALS

Syn. Rutile	.330
Diamond	.044
Strontium titanate	.109
Cubic zirconia	.060
GGG	.038
Zircon (High and Medium)	.038
Andradite	.057
YAG	.028
Zircon (Low)	Weak
Spessartite	.027
Almandite	.024
Corundum	.018
Syn.Corundum	.018
Rhodolite	.026
Pyrope	.027
Chrysoberyl	.015
Grossularite	.028
Syn. Spinel	.020
Spinel	.020
Idocrase	.019
Zoisite	.021
Spodumene	.017
Peridot	.020
Andalusite	.016
Tourmaline	.017
Topaz	.014
Beryl	.014
Syn. Emerald	.014
Quartz	.013
Orthoclase	.012
Calcite	.017
Glass (Silica)	.010
(Crown)	.016
Fluorite	.007

(CS, #7, p. 17)